3.4 Constraints

The minimization of cost in ReEDS is subject to a large number of different constraints, involving limits on resources, transmission constraints, ancillary services, and pollution, along with requirements to meet capacity and generation needs. Unless specifically noted otherwise (see, for example, the wind resource limit below), these constraints apply to new generating capacity built in the time period being optimized.

The constraint name is shown with the subscripts over which the constraint applies. For example, in the constraint immediately below, the subscript *'c, i, l'* immediately following the name of the constraint implies that this constraint is applied for every class of wind *c*, every region *i*, and every location *l*. Because there are 356 regions, five classes of wind, and three locations, this first type of constraint is repeated 5,340 times (356x5x3). The variables may have the same subscripts, but, for simplicity, the subscripts of the constraint are omitted in the variables.

3.4.1 Constraints on Wind

Wind Resource Constraint: all wind capacity installed must be less than the total wind resource in the region.

$WIND\_RES\_UC_{c,i,l}$

$$\text{Wtur} + \textit{Wtur\_old} \quad \leq \quad \textit{total wind resource}$$

Wind Transmission Constraint: New wind power transmitted from a region must be less than or equal to the total amount of new wind capacity built in that region.

$WIND\_2\_GRID_{c,i,l}$

$$\sum_{j} \text{WN}_j \quad \leq \quad \text{Wtur}$$

Wind Curtailments: Wind must be less than the load.

$WIND\_DEMAND\_LIMIT_{n,m}$

$$\sum_{c,i,j,l}^{j \in n} \text{WN}_{c,i,j,l} \quad \leq \quad (\textit{load} + \textit{STORin})$$

3.4.2 Constraints on CSP

CSP Resource Limit: all CSP capacity installed must be less than the total solar resource in the region.

$CSP\_RES\_UC_{cCSP,i}$

$$\text{CSPtur} + \textit{CSPtur\_old} \quad \leq \quad \textit{total CSP resource}$$

CSP Transmission Constraint: New CSP transmitted from a region must be less than or equal to the total amount of new CSP capacity built in that region.

$CSP\_2\_GRID_{cCSP,i}$

$$\sum_{j} \text{CSPN}_j \quad \leq \quad \text{CSPtur}$$

3.4.3 General Renewable Constraints

Limits on Existing Transmission: New wind and CSP imported into a region can not exceed the amount of transmission available to transport it.

WIND_interregion_trans$_j$

$$\sum_{c,i,l} \mathrm{WN}_{c,i,l} + \sum_{cCSP,i} \mathrm{CSPN}_{cCSP,i} \quad \leq \quad \sum_{i} \textit{available transmission capacity}_i$$

RPS Requirement: Total national annual renewable generation must exceed a specified fraction of the national electricity load or a penalty (defined here, levied in the objective function) must be paid on the shortfall.

RPSConstraint

$$\begin{aligned}
&\sum_{c,i,j,l} (\mathrm{WN}_{c,i,j,l} + \mathit{WN_old}_{c,i,j,l}) \cdot \mathit{CF}_{c,i,l} - \sum_{n} \mathrm{WSurplus}_n \quad + \\
&\sum_{cCSP,i,j} (\mathrm{CSPN}_{st} + \mathit{CSPN_old}_{c,i,j}) \cdot \mathit{CF}_{cCSP} \quad + \\
&\sum_{n} (\mathrm{CONVgen}_{n,hydro} + \mathrm{CONVgen}_{n,geothermal} + \mathrm{CONVgen}_{n,biopower} + \mathrm{CONVgen}_{n,lfill} + \mathrm{CONVgen}_{n,distPV}) \quad + \\
&\mathrm{RPSshortfall} \quad \geq \\
&\mathit{RPS\ fraction} \cdot \Big(\sum_{c,i,j,l} (\mathrm{WN}_{c,i,j,l} + \mathit{WN_old}_{c,i,j,l}) \cdot \mathit{CF}_{c,i,l} - \sum_{n} \mathrm{WSurplus}_n \quad + \\
&\sum_{cCSP,i,j} (\mathrm{CSPN}_{st} + \mathit{CSPN_old}_{c,i,j}) \cdot \mathit{CF}_{cCSP} \quad + \\
&\sum_{n,q} \mathrm{CONVgen}_{n,q} \Big)
\end{aligned}$$

Similar RPS constraints exist at the state level and can be seen in the detailed model description, below. It should be noted that legislated requirements of this type—emissions, RPS, etc.—can be constrained at any of the regional levels contained in the model, though such constraints are not generally included in the current version.

3.4.4 Constraints on System Operation

Generation Requirement: Generation plus net imports plus net storage must meet load requirements in each balancing authority in each time-slice.

LOAD_PCA$_{n,m}$

$$\sum_{q} \text{CONVgen}_{q} + \sum_{p} \text{CONVT}_{n,p,m} \quad +$$

$$\sum_{c,i,j,l}^{j \in n} (\text{WN}_{c,i,j,l} + \textit{WN\_old}_{c,i,j,l}) \cdot \textit{CF}_{c,m,l} - \text{WSurplus} \quad +$$

$$\sum_{cCSP,i,j}^{j \in n} (\text{CSPN}_{st} + \textit{CSPN\_old}_{c,i,j}) \cdot \textit{CF}_{cCSP,m} \quad +$$

$$\sum_{st} \text{STORout}_{st} \quad = \quad \textit{load} + \sum_{p} \text{CONVT}_{p,n,m} + \sum_{st} \text{STORin}_{st}$$

Reserve Margin Requirement: Dispatchable capacity plus capacity value of wind and CSP plus storage capacity plus net contracted firm capacity must exceed the peak annual load plus a reserve margin.

RES_MARG$_{rto}$

$$\sum_{n,q}^{n \in rto} \text{CONV}_{n,q} \quad +$$

$$\sum_{c,i,j,l}^{j \in rto} \text{Wtur}_{c,i,j,l} \cdot \textit{CV}_{c,i,l} \quad +$$

$$\sum_{cCSP,i,j}^{j \in rto} \text{CSPtur}_{cCSP,i,j} \cdot \textit{CV}_{cCSP,i} \quad +$$

$$\sum_{n,st}^{n \in rto} \text{STOR}_{n,st} \cdot \textit{CV}_{n,st} \quad +$$

$$\sum_{n,p}^{n \in rto} (\text{CONTRACTcap}_{p,n} - \text{CONTRACTcap}_{n,p}) \quad \geq \quad \sum_{n}^{n \in rto} \textit{peak load}_{n} \cdot (1 + \textit{reserve margin}_{n})$$

Operating Reserve Requirement: Spinning reserve plus quick-start capacity plus storage capacity must meet the normal operating reserve requirement plus that imposed by wind.

OPER_RES$_{rto,m}$

$$\sum_{n,q}^{n \in rto} (\text{SR}_{n,q} + \text{QS}_{n,q}) + \sum_{st} \text{STOR\_OR}_{n,st} \quad \geq \quad \sum_{n}^{n \in rto} \textit{normal operating reserve reqt}_{n} + \sum_{c,i,l} \textit{wind-induced operating reserve reqt}_{c,i,l}$$

Spinning Reserve Constraint: Spinning reserve available in a given time-slice is limited to a fraction of the peak seasonal output of that plant.

SPIN_RES_CAP$_{n,m,q}$

$$\text{SR} \quad \leq \quad \text{CONVgen}_{seasonpeak} \cdot \textit{SR fraction}_{q}$$

Capacity Dispatch Constraint: Conventional capacity (after outages) must be sufficient to supply all the firm power, spinning reserve, and quickstart capacity demanded in each time-slice.

CAP_FO_PO$_{n,m,q}$

$$\text{CONVgen} + \text{SR} + \text{QS} \quad \leq \quad \text{CONV} \cdot (1 - \textit{outage rate})$$

Minimum Load Constraint: Conventional plants with minimum load requirements can not operate below the prescribed level.

MIN_LOADING$_{n,m,q}$

$$\text{CONVgen} \quad \geq \quad \text{CONVgen}_{peak} \cdot \textit{minimum load fraction}$$

3.4.5 Constraints on Storage

Energy Balance: Energy discharged from storage must not exceed the energy used to charge storage (after accounting for round-trip efficiency) within a single season.

ENERGY_FROM_STORAGE$_{n,s,st}$

$$\sum_{m}^{m \in s} \text{STORout}_m \quad \leq \quad \sum_{m}^{m \in s} \text{STORin}_m \cdot \textit{round-trip efficiency}$$

Dispatch Constraint: Storage capacity (after outages) must be sufficient to supply all charging power, discharging power, and operating reserve demanded in each time-slice.

STORE_FO_PO$_{n,m,st}$

$$\text{STORout} + \text{STORin} + \text{STOR\_OR} \quad \leq \quad \text{STOR} \cdot (1 - \textit{outage rate})$$

3.4.6 Others

Hydropower Energy Constraint: The energy generated from hydroelectric capacity must conform to the historical availability of water.

HYDRO_ENERGY$_n$

$$\sum_{m} \text{CONVgen}_{m,hydro} \quad \leq \quad \textit{annual hydro energy available}$$

SO_2 Scrubber Constraints: Combined capacity of the scrubbed and unscrubbed coal plants must be equal to the total of the two from the last period minus retirements. Furthermore, unscrubbed coal capacity can not exceed the unscrubbed capacity of the last period minus retirements. This allows the unscrubbed to become scrubbed, i.e., the unscrubbed capacity can decrease but the total can not.

SCRUBBER$_n$

$$\begin{aligned} \text{CONV}_{scrubbedcoal} + \text{CONV}_{unscrubbedcoal} &= CONVold_{scrubbedcoal} \\ &\quad + CONVold_{unscrubbedcoal} - retirements \\ \text{-and-} & \\ \text{CONV}_{unscrubbedcoal} &= CONVold_{unscrubbedcoal} - retirements \end{aligned}$$

Emissions Constraint: National annual emissions of each pollutant (CO_2, SO_2, NO_x, Hg) by all generators do not exceed their respective national caps.

EMISSIONS$_{pol}$

$$\sum_{n,q} \text{CONVgen}_{n,q} \cdot emissions_q + \sum_{n} \text{STORout}_{n,CAES} \cdot emissions_{CAES} \leq emissions\ limits$$

Transmission Constraint: Transmission between balancing authorities must be sufficient to carry all wind, CSP, and conventional energy being sent between those areas.

CONV_TRAN_PCA$_{n,p,m}$

$$\text{TPCAN} \geq \text{ReT} + \text{CONVT}$$